# Dynamics of Heavy Ion Reactions using the Energy Density Formalism

Raj Kumar*

*Department of Physics, Panjab University, Chandigarh - 160014, INDIA.*

## Introduction

The Dynamical Cluster-decay Model (DCM) of Gupta and collaborators [1], together with the Wong formula, have been advanced to study the heavy ion reaction dynamics. The DCM, based on the well known Quantum Mechanical Fragmentation Theory (QMFT), has been developed to study the decay of hot and rotating compound nucleus (CN) with effects of deformations and orientations of incoming and/or outgoing nuclei included. In DCM, the decay fragments are considered to be preformed with probability $P_0$ before penetrating the interaction barrier, whereas the Wong formula is based simply on the barrier penetrability $P$. For the capture, equivalently, quasi-fission reactions, the $\ell$-summed extended-Wong model of Gupta and collaborators [2] is shown to be the same as the DCM expression, since for each angular momentum $\ell$, $P_0^\ell$=1 for the incoming channel not having lost its identity. For the nuclear interaction potential, the proximity potential of Blocki's pocket formula or from the more microscopic approach of semi-classical extended Thomas-Fermi (ETF) model [3] is used.

## Results

First, the DCM is applied to recent data on the decay of the compound systems $^{118,122}$Ba* at a relatively low bombarding energy of 5.5 MeV/A, using the proximity pocket potential of Blocki *et al.*. Since these are heavier compound systems, a complete mass fragmentation spectrum is observed experimentally. The DCM gives [4] an overall good description of the observed data on cross-sections, except for a small narrow region of mass fragments $8 \leq Z_L \leq 15$. Furthermore, the DCM shows an interesting in-built characteristic of presenting different behaviors for different mass regions of decay products, namely, the light intermediate mass fragments (IMFs), the heavy mass fragments (HMFs) and the symmetric and near symmetric fission fragments (SF and nSF), a property required to be assumed in the (BUSCO and GEMINI) statistical model calculations. In DCM, this property is assimilated via the neck-length parameter which fixes the $\ell_{max}$-value, used as a parameter in the BUSCO and GEMINI codes.

Next, the universal function of nuclear proximity potential is obtained [3] for the Skyrme nucleus-nucleus interaction in the semiclassical ETF approach. The resulting nuclear proximity potential reproduces, with in less than $\sim$ 1 MeV of difference [3], the "exact" Skyrme nucleus-nucleus interaction potential in semiclassical approach. An application of the corresponding interaction potential to fusion excitation functions shows clearly that the parameterized universal function of nuclear proximity potential substitutes the "exact" potential in Skyrme energy density formalism based on ETF method.

Using the above noted proximity potential, obtained in Skyrme energy density formalism (SEDF) based semiclassical ETF approach, with densities added in frozen approximation, and effects of deformations and orientations of nuclei included, the barrier modification effects are studied by using the extended-Wong formula [2, 5], for the capture and fusion-evaporation cross-section data for Ca- and Ni-induced reactions. The later are known for fusion hindrance phenomenon in coupled-channels calculations (ccc). Frozen density, i.e. sudden approximation without

*Electronic address: rajkumarfzr@gmail.com; Present address: SPMS, Thapar University, Patiala - 147004.

exchange effects, compared to with exchange terms included, is found to give more realistic barriers [5] for the proximity potential obtained in the semiclassical ETF approach of SEDF. Taking advantage of the fact that different Skyrme forces give different barriers (height, position and curvature), we use the $\ell$-summed extended-Wong model [2] where the Skyrme force is chosen with proper barrier characteristics, *not-requiring* additional "barrier lowering" or "barrier narrowing", for a best fit to cross-section data at sub-barrier energies. The method is applied specifically to capture cross-sections from $^{48}$Ca+$^{238}$U, $^{244}$Pu, and $^{248}$Cm reactions and to fusion-evaporation cross-sections from $^{58}$Ni+$^{58}$Ni, $^{64}$Ni+$^{64}$Ni, and $^{64}$Ni+$^{100}$Mo reactions. Interestingly, whereas the capture cross-sections in $^{48}$Ca+$^{238}$U and $^{48}$Ca+$^{244}$Pu reactions could be fitted to any force, such as SIII, SV and GSkI (by allowing a small change of couple of units in the deduced $\ell_{max}$ values), the fusion-evaporation cross-sections in Ni-induced reactions required different Skyrme forces for the best fit to data. In other words, just as for the pocket formula of nuclear proximity potential [2], for the ETF-based proximity potential also, no barrier modification effects are required for the Ca-based capture cross-sections in $\ell$-summed extended-Wong model, but the same are essential for the fusion-evaporation cross-sections in Ni-based reactions displaying fusion-hindrance in ccc, taken care here by the use of different Skyrme forces for different reactions. Note, however, that no single Skyrme force was able to reproduce the data simultaneously for all the above mentioned three Ni-based reactions, though more than one Skyrme force could fit equally well the same data.

With in the SEDF based semiclassical ETF approach, for Skyrme forces SIII and GSkI, used for calculating the nuclear proximity potential under frozen density approximation, the DCM is then used to study the decay of hot and rotating compound nucleus $^{164}$Yb$^*$ formed in $^{64}$Ni+$^{100}$Mo reaction at both below- and above-barrier energies. Earlier the same study is made with the use of pocket formula of Blocki *et al.* by myself and collaborators [6]. There is only one parameter in this model, namely, the neck-length parameter, which varies smoothly with the temperature of compound nucleus at both below and above-barrier energies, and its value remains within the range of validity of proximity potential. A best fit to data is obtained for two different neck-length parameters, one for light-particles (LPs), the evaporation residues, and another for all other decay channels, the fusion-fission ($ff$) cross-section. The barrier height corresponding to the neck length parameter for LPs (or ff), gives "barrier lowering" in a straight-forward way for the best fitted fusion-evaporation (or ff) cross-sections in DCM with Skyrme force SIII and GSkI, and, contrary to the (statistical model) analysis of experimental data, results in largest contribution for $1n$ emission. The effect of Skyrme forces on barrier modification is also studied. A further study is called for both the LPs and $ff$ channels.

## Acknowledgments

I am thankful to Prof. Raj K. Gupta, my thesis supervisor, and the DST and CSIR, New Delhi, for fundings in terms of a JRF and SRF for myself.

## References

[1] R. K. Gupta, Lecture Notes in Physics 818, *Clusters in Nuclei*, ed C. Beck, Vol. I, (Springer Verlag) p 223 (2010).

[2] R. Kumar, M. Bansal, S. K. Arun and R. K. Gupta, Phys. Rev. C **80**, 034618 (2009).

[3] R. K. Gupta, D. Singh, R. Kumar and W. Griener, J. Phys. G: Nucl. Part. Phys. **36**, 075104 (2009).

[4] R. Kumar and R. K. Gupta, Phys. Rev. C **79**, 034602 (2009).

[5] R. Kumar and R. K. Gupta, J. Phys.: Conf. Series, (2011) in press.

[6] S. K. Arun, R. Kumar and R. K. Gupta, J. Phys. G: Nucl. Part. Phys. **36**, 085105 (2009).